Proc. Natl. Acad. Sci. USA
Vol. 94, pp. 2783–2784, April 1997
From the Academy

This paper serves as a summary of a symposium session as part of the Frontiers of Science series, held November 7–9, 1996, at the Arnold and Mabel Beckman Center of the National Academies of Sciences and Engineering in Irvine, CA.

The epoch of galaxy formation

DAVID N. SPERGEL*, SIMON J. LILLY†, AND CHARLES STEIDEL‡

*Department of Astrophysical Sciences, Princeton University, NJ 08544; †Department of Astronomy, University of Toronto, 60 George Street, Toronto, ON Canada MS 3H8; and ‡Department of Astronomy, 105-24, California Institute of Technology, Pasadena, CA 91125

Recent advances in technology have enabled astronomers to observe fainter, and more distant, galaxies and to study the processes of galaxy formation and evolution. Recent observations suggest that the bulk of the stars in the universe formed between $z = 3$ ($\sim 1 \times 10^9$ years after the big bang) and the present. The star formation rate appears to have peaked at $z \sim 1$–2 (~ 2–4×10^9 years after the big bang). While galactic disks appear to form primarily around $z = 1$, the central regions of spiral galaxies and most elliptical galaxies appear to have been assembled at higher redshift.

Our Place in the Universe

Our Galaxy is a typical spiral galaxy: its young and intermediate age stars make up a rotating disk, while its central spheroid is composed primarily of older stars. Astronomers divide galaxies into two broad morphological classes: elliptical galaxies and spiral galaxies. Elliptical galaxies are similar to spheroids of spirals and are composed mostly of older stars. Most galaxies are part of some small group of galaxies and these small groups are clustered as part of a rich web of "filaments," "walls," and "voids." How did this rich structure of stars and galaxies arise out of a nearly uniform early universe? When did the typical star form? How are stars assembled together to form galaxies? Much of the research in cosmology is driven by a desire to answer these questions and related questions.

By observing distant galaxies, astronomers are able to probe earlier epochs in the history of the universe. Because light travels at a finite speed, we see objects not as they are today, but as they were at an earlier epoch. Astronomers are able to estimate the distance to a galaxy by measuring its "redshift," $z = (\lambda_o - \lambda_e)/\lambda_e$, where λ_e is the laboratory wavelength of the line emitted at epoch, t_e, and λ_o is the observed wavelength of the line at the present epoch, t_0. Big bang cosmology relates redshift to emission epoch. The relationship is simplest in a "flat" universe, $t_e = t_0 \cdot (1 + z)^{-3/2}$. At low redshift, this relationship reduces to the Hubble law: $z = H_0 D$, where H_0 is the "Hubble constant" and D is the distance to the galaxy. Our best estimates are that the universe is between 12 and 16 billion years old (1). The exact relationship between age and redshift depends on the mass density and composition of the universe.

The Epoch of Galaxy Formation?

The advent of large telescopes and more sensitive detectors have enabled astronomers to obtain high quality spectra of distant galaxies, powerful probes of galaxy properties. The redshift of the spectral lines determines the distance and age of the galaxy and the strength of the spectral lines depends upon the chemical composition of the galaxy and its stellar population. Astronomers complement this spectral information with high resolution images from the Hubble Space Telescope.

Recent studies (2, 3) that combine spectroscopic and morphological information probe the universe back to $z = 1$ and use the same criterion to select distant and nearby galaxies. These surveys find that the red components of galaxies, the spheroids and ellipticals, do not show much evidence for evolution: there are roughly the same number of bright elliptical galaxies today as there were when the universe was half its present age. On the other hand, the blue components of galaxies appear to evolve rapidly: the typical disk at $z = 1$ had a much higher surface brightness then today and was much bluer. These properties imply a much higher rate of star formation in the past. When averaged over all galaxies, the star formation rate at $z = 1$ was roughly 10 times the present star formation rate. Life in the universe at $z = 1$ was generally more dramatic: Le Fevre *et al.* (4) find an increased rate of galaxy mergers at high redshift.

Direct observations of galaxies are complemented by studies of quasar absorption lines. Quasars are bright nearly point-like sources of light, which many think are due to the accretion of gas onto supermassive black holes at the centers of galaxies. The spectra of quasars are nearly featureless; thus astronomers can detect absorption due to intervening clouds of gas called QSO absorbers.

By looking around the quasars, Steidel *et al.* (5) has been able identify the galaxies that are responsible for the absorption lines. These galaxies, selected by their absorbtion properties, appear similar to the galaxies selected by their emission properties at blue wavelengths. The number of QSO absorbers drops dramatically between $z = 1$ and the present, possibly due to the consumption of gas into stars. The inferred gas consumption rates is consistent with the star formation rates found in the redshift surveys (6). The QSO absorption line studies also show dramatic increases in the abundances of carbon and other heavy elements. Because the same massive stars that produce both most of the ultraviolet light and carbon and the other heavy elements, the 100-fold increase in carbon abundance between $z = 3$ and $z = 1$ implies that the bulk of the stars formed at $1 < z < 3$.

It is more difficult to probe higher redshifts as distant objects are much dimmer than nearby galaxies. The difficulty of detecting galaxies at $1.5 < z < 3$ is further exacerbated by the galaxy spectra being nearly featureless between 1300 and 3500 A, which redshifts into the most sensitive range of optical wavelengths (3,200–10,000 A).

At $z > 3$, a very strong spectral feature enables astronomers to detect very distant galaxies: hydrogen absorption at 912 A. When this feature redshifts into wavelengths accessible from the ground, it becomes possible to use it to identify candidate distant objects. Until recently, it has been very difficult to obtain spectra of these high redshift galaxies, as their surface brightnesses are typically 1% of the brightness of the atmosphere. By using a multislit spectograph, which can simulta-

0027-8424/97/942783-2$2.00/0
PNAS is available online at **http://www.pnas.org**.

neously observe multiple galaxies, at the new 10-meter Keck telescope, astronomers have been able to measure redshifts of this distant galaxies for the first time (7, 8).

These high redshift galaxies are morphologically similar to the spheroids and ellipticals seen at lower redshift (9). Interpreting these observations are difficult as we have few nearby galaxies have been observed in the far ultraviolet wavelengths that correspond to the rest wavelength of these distant objects. However, it is tempting to believe that we are seeing the central portions of galaxies being assembled at high redshift.

The inferred rate of star formation at $z \sim 3$ is comparable to the present star formation and much lower than the star formation rate at $z = 1$. Thus, a coherent picture is beginning to emerge from a wide range of surveys: the star formation rate appears to have peaked between a redshift of 1 and 3. This period of rapid star formation exhausted most of the cosmic supply of neutral gas and polluted the remaining gas with "heavy" elements, such as carbon, oxygen, and nitrogen. It is intriguing that the number density of bright quasars also peaked during this epoch.

The Future: Infrared Studies of the More Distant Past

Our view of the universe remains limited by our observational tools and the earth's atmosphere. Most interesting spectral lines are at optical and near infrared wavelengths, thus, it is difficult to study galaxies at $1 < z < 2$ and high redshift. In distant galaxies, these lines are redshifted further into the infrared, where it is very difficult to observe from the ground. In 1997, an infrared camera (sensitive at 1–2 microns) will be added to Hubble Space Telescope, which will improve our ability to study the universe at these wavelengths. Currently, astronomers are considering the possibility of the building a "Next Generation Space Telescope" that operates in the 1- to 10-μm wavelength range. This instrument, if built, will be able to see yet more distant galaxies and probe deeper into the history of the universe.

1. Spergel, D. N., Bolte, M. & Freedman, W. (1997) *Proc. Natl. Acad. Sci. USA* **94,** in press.
2. Lilly, S. J., Tresse, L., Hammer, F., Crampton, D. & Le Fevre, O. (1995) *Astrophys. J.* **455,** L108–L111.
3. Lilly, S. J., Le Fevre, O., Hammer, F. & Crampton, D. (1996) *Astrophys. J.* **460,** L1–L4.
4. Le Fevre, O., Hudon, D. Lilly, S. J., Crampton, D., Hammer, F. & Tresse, L., in *Proceedings of the Herstmonceux Conference*, in press.
5. Steidel, C. C., Dicksinson, M. & Persson, S. E. (1994) *Astrophys. J.* **437,** L75–L78.
6. Fall, S., Charlot, S. & Pei, Y. C. (1996) *Astrophys. J.* **464,** L43–L46.
7. Steidel, C. C., Giavalisco, M., Dicksinson, M. & Adelberger, K. L. (1996) *Astron. J.* **112,** 352–358.
8. Madau, P., Ferguson, H. C., Dicksinson, M. E., Giavalisco, M., Steidel, C. C. & Fruchter, A. (1996) *Mon. Not. R. Astron. Soc.* **283,** 1388–1404.
9. Giavalisco, M., Steidel, C. C. & Macchetto, F. D. (1996) *Astrophys. J.* **470,** 189–194.